

*On the Origin of the Indo-Gangetic Trough, commonly called
the Himalayan Foredeep.*

By Colonel Sir SIDNEY BURRARD, K.C.S.I., R.E., F.R.S., Surveyor-General
of India.

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1. *The Question under Discussion.*

The plains of Northern India consist of alluvial deposits brought down by the Rivers Indus and Ganges. These plains conceal from our view a deep trough that has been formed in the solid rock of the Earth's crust. The trough is bounded on the north by mountains of the tertiary age and on the south by an ancient pre-tertiary tableland. North of the trough the Earth's crust has undergone continual compression, disturbance, and uplift since the beginning of the tertiary age; south of the trough it has remained undisturbed since the close of the palæozoic era.* On fig. 1 are shown the Indo-Gangetic trough, the mountainous area on its north, and the tableland on its south.

From the writings of Suess, the Indo-Gangetic trough has come to be called the Himalayan foredeep. In this paper I am proposing to consider one question only, namely, the origin of the Himalayan foredeep.

2. *The Zone of Low Density in the Crust.*

In 1912 I published a paper in which I endeavoured to show that a zone of low density underlies the Indo-Gangetic alluvium and skirts the southern foot of the Himalaya Mountains.†

The existence of this line of low density in the crust has not been disputed. Its significance lies in the fact that it furnishes an argument against Prof. Suess's theory of Himalayan formation. Prof. Suess held that the mountains of Tibet and Persia are advancing southwards in a great series of folds.‡

Mr. Hayden, Director of the Geological Survey of India, writes that the great series of folds in Central Asia are supposed to have been caused by a horizontal thrust from the north.§

* 'Geology of India,' p. 2, R. D. Oldham.

† Survey of India Professional Paper No. 12, 'On the Origin of the Himalayan Mountains.'

‡ 'The Face of the Earth,' vol. 1, p. 596.

§ 'Sketch of Geography and Geology,' p. 48.

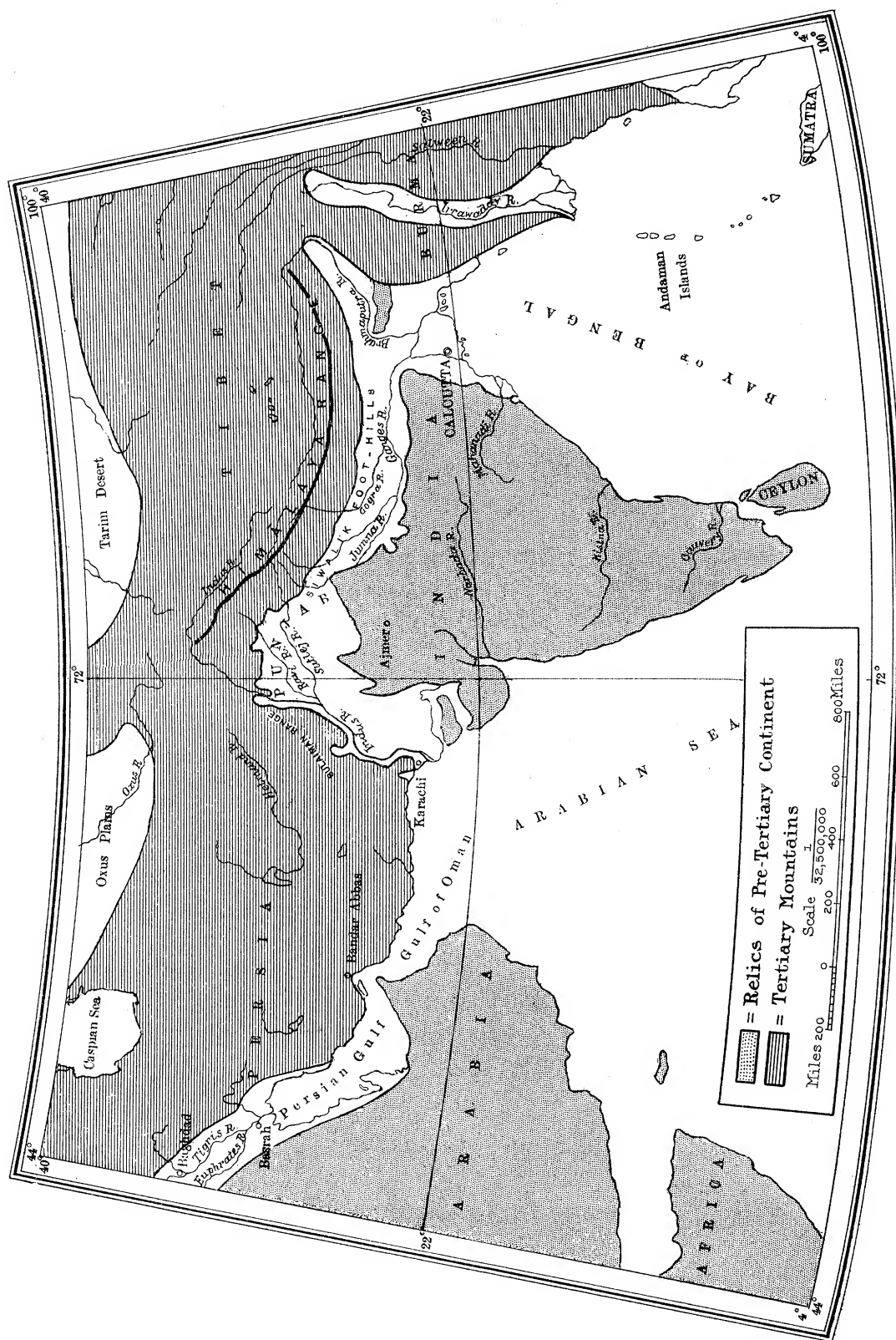


FIG. 1.

Mr. Middlemiss speaks of "the well-established forward march" of the Himalaya range.*

Mr. Oldham states that there has been a southerly advance of the margin of the hills since the Upper Siwalik age.†

It will thus be seen that geological authorities have adopted the theory that the Himalayas are advancing southwards towards the foredeep.

The discovery of a zone of deficient density in the crust skirting the Himalayan foot led me to ask this question: Is the existence of this long line of deficient density lying south of the Himalayas compatible with the view that the crust of Asia is being pushed southwards by a tangential force from the north?

My conclusion was that the existence of this deficiency of matter throughout the northern zone of the Indo-Gangetic alluvium was a strong argument against the theory that the Himalaya Mountains are moving southwards.

The Himalayas are a portion of the plateau of Perso-Tibet, and this plateau appears to me to owe its elevation partly to direct vertical uplift and partly to horizontal thrusts. Horizontal forces from the north and the south seem to have squeezed the plateau between them; on the north side of the plateau the horizontal thrust seems to have emanated from the low-lying plains of the Oxus and from the deserts of Tarim (fig. 1), and to have acted in a southerly direction; on the south side the horizontal thrust seems to have emanated from the low-lying plains of the Euphrates, Indus, and Ganges, and to have acted in a northerly direction.

I closed my paper of 1912 by suggesting that the Himalayan foredeep had been caused by a tension in the crust and that it was, in fact, a crustal opening or rift.

I made use in places of the word "crack." The objection has since been raised that the sub-crust of the Earth is in too viscous a state to "crack." It has been stated that by the use of the word "crack" I have assumed that the sub-crust is solid, and behaves like a solid. I do not, however, wish to make any such assumption, nor do I wish to insist on any particular word. Here, in front of the Himalayas is a deep trough; this trough has been attributed by some authorities to horizontal "compression" of the Earth's crust; it has been attributed by others to "depression" of the crust by the weight of alluvial deposits.

I ask that the hypothesis of an "opening" of the crust may be considered side by side with these hypotheses of "compression" and "depression." If the sub-crust is regarded as solid, the word "crack" will define my meaning;

* 'The Kangra Earthquake,' p. 340.

† 'Geology of India,' p. 470, R. D. Oldham.

if the sub-crust is regarded as viscous, the words "tension" or "stretching" or "opening" can be substituted for the word "crack."

3. The Siwalik Foot-hills.

Wedged in between the Himalaya Mountains and the Indo-Gangetic trough is a narrow zone of low foot-hills called the Siwalik Hills. It is open to question whether these hills ought to be classed with the mountains or with the "foredeep."

The materials composing the Siwalik Hills are so similar to the recent alluvial deposits that they are regarded as an elevated portion of the Indo-Gangetic plains.

Compared with the great ranges of the Himalaya and Tibet, the Siwalik range is insignificant; compared with the alluvial deposits filling the Indo-Gangetic depression, the Siwalik masses are small. In discussions of Himalayan questions, the Siwalik Hills assume importance, because they are always before our eyes. Popular and crowded European stations are situated in the outer hills, and we are apt to attach undue importance to our surroundings.

But in the formation of the Himalaya Mountains on the one side and of the Himalayan foredeep on the other, these small intermediate Siwalik Hills are mere secondary effects.

The strata of which the Siwaliks are composed date back to early tertiary times, and throughout this period have been subjected to horizontal compression and to disturbance. Although they have undergone long-continued tangential compression, these hills have not been elevated into mountains like the neighbouring Himalaya. The explanation of this difference is, I think, that the Himalaya Mountains have been upraised by forces acting at great depths in the Earth's sub-crust, whilst the Siwalik Hills have been formed out of the outer crust. The foundations of the Himalaya Mountains extend downwards to depths perhaps of 50 miles or more; the Siwalik Hills are wholly superficial. I attribute the compression of the Siwalik strata to the opening of the Himalayan foredeep; as the foredeep opens, the superficial strata along its northern edge are squeezed against the Himalayan Mountains.

4. Mr. Oldham's Explanation of the Himalayan Foredeep.

The explanation of the origin of the Himalaya Mountains given in Mr. Oldham's 'Geology of India,' pages 471-474, is based upon the Rev. O. Fisher's theory that the crust of the Earth is floating upon a fluid magma. It would be beyond the scope of this paper to enter into the details of the

Fisher-Oldham theory of mountains, as I wish to confine myself to Mr. Oldham's recent paper in these 'Proceedings,' vol. 90. The main feature of that paper is his discussion of the Indo-Gangetic trough. In his opinion this trough has been created by the sinking of the crust under the weight of the alluvial deposits brought down from the mountains by the rivers.

To quote his own words :—"The load thrown on D (the alluvial plains) will cause it to sink specially in the neighbourhood of A (the Himalayas) where the load is greatest, till the magma displaced by the lower surface of the crust is sufficient to float the load."*

Mr. Oldham's explanation of the Indo-Gangetic trough is that it is a "depression" due to the sinking of strata under their own weight.

Prof. Suess's explanation is that this trough is a downward bend of the crust of the Earth in front of the advancing Himalayan wave. Mr. Oldham attributes the trough to vertical subsidence and "depression"; Prof. Suess attributes the trough to horizontal "compression" from the north.†

I have ventured to suggest that the trough has been due neither to "depression" under weight of load, nor to "compression" by horizontal force, but to the opening of the sub-crust under "tension." Three different hypotheses have thus been submitted for consideration. Of these Suess's hypothesis of "compression" has been severely criticised by Prof. James Geikie in Chapter XI of his recent work, 'Mountains—their Origin, Growth, and Decay.'

In this paper I propose to consider the two hypotheses of "depression" and of "tension" and to explain my reasons for thinking that the hypothesis of a sub-crust opening under tension is more in accordance with observed facts than the idea of strata being depressed under their own weight.

Mr. Oldham accepts the existence of the geodetic line of low density, and his explanation of that line, *i.e.* of the Himalayan foredeep, is this: 15,000 to 30,000 feet of sediment have been deposited by the Himalayan rivers at the foot of the mountains; the Earth's crust has been insufficiently rigid to support these deposits, and the latter have continued to sink deeper and deeper into the solid crust.

With reference to this theory of strata sinking under their own weight I beg to invite the attention of geologists to the following considerations :—

* 'Geology of India,' p. 474, R. D. Oldham.

† Mr. Oldham sees evidence of compression in the Siwalik Hills, but he thinks that the compression caused by the advance of the Himalayas "will *elevate* the marginal deposits"; he does not attribute the trough-like form of the Himalayan foredeep to "compression."

5. *First Consideration: The Weight of the Load.*

If alluvium of density 2.1 is resting in rock of density 2.7, as Mr. Oldham assumes, like an iceberg rests upon water, the portion above sea-level will be two-sevenths of that below sea-level; if alluvium has been pressed down by its own weight to a depth of 20,000 feet, displacing a denser substance, we ought to see 5700 feet of it standing above sea-level; if it has been pressed down by superincumbent weight to 30,000 feet, there should be 8600 feet above sea-level. The actual height of Jalpaiguri, Mr. Oldham's station on the alluvium, is, however, only 280 feet above sea-level.

Mr. Oldham's assumed sub-crustal magma is denser than the crust floating upon it. If my calculations are to be made rigorous, we must compare the weight of the alluvium with the weight, not of displaced rock, but of displaced magma; and the alluvium will then be computed to be standing at a greater height even than I have deduced above. The fact that it does not stand at any such height is a strong argument against the hypothesis of a quasi-liquid interior for the Earth as well as against the general idea of sinking strata.

6. *Second Consideration: The Tuscarora Deep.*

The Himalayan foredeep resembles the Japanese foredeep, commonly known as the Tuscarora Deep; these two foredeeps, though differing in certain particulars, have so many features in common that they are believed to have originated from similar causes. The Himalayan foredeep is now filled with alluvium, the Japanese foredeep is still filled with sea-water. The Japanese foredeep will possibly be filled with sedimentary deposits in time, but its existing trough-like form cannot be attributed now to the weight of deposits. The existence of a long trough, between 5 and 6 miles deep, that has obviously not been caused by deposits, is a strong proof that the Himalayan foredeep has also originated independently of the deposits which now fill it.

7. *Third Consideration: The Submarine Swatches.*

To the best of my belief the Indo-Gangetic trough is continued out to sea, both on the east and on the west. I attach two small charts (figs. 2 and 3), which show the submarine troughs extending seawards from the deltas of the Ganges and of the Indus.* These troughs have not yet been filled with alluvial deposits, they are antecedent to the deposits. It is a significant fact that in Indian waters the only rivers that are continued seawards by submarine troughs are the Ganges and the Indus. The Godavari, the Caveri, the Kistna, have no such troughs extending beyond

* 'Geological Magazine,' vol. 10, No. 591, p. 387, September, 1913.

their deltas. The submarine troughs of the Ganges and Indus will doubtless be filled with deposits in time, and our successors may then be led to believe that the troughs were created by the weight of these deposits.

In early tertiary times, before the existing loads of silt had been brought

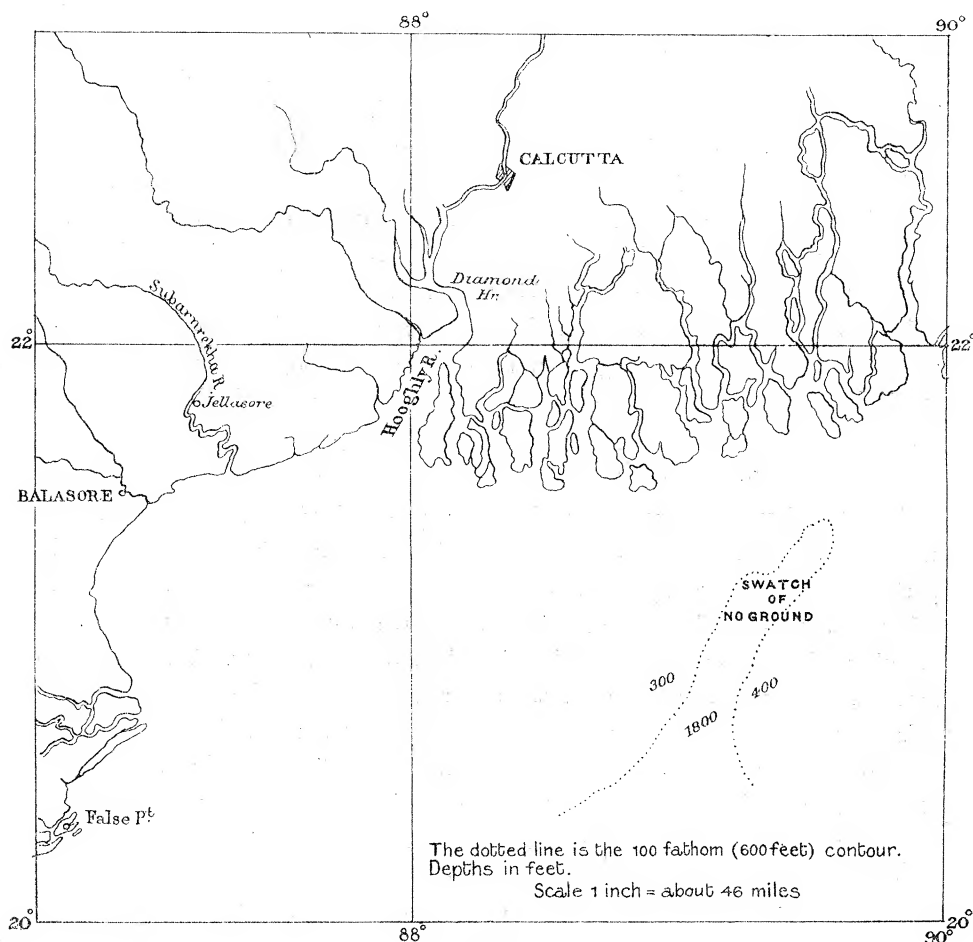


FIG. 2.

down from the mountains by the rivers, the Indo-Gangetic trough had already been formed and was a narrow arm of the sea.*

8. *Fourth Consideration : How Rivers Deposit their Loads.*

Mr. Oldham writes that the load of silt thrown on to the plains will cause them to sink, "especially in the neighbourhood of the Himalayas where the

* H. H. Hayden, 'Sketch of Geography and Geology of the Himalayas,' p. 255. See so charts in McCabe's 'Story of Evolution.'

load is greatest." He assumes, therefore, that a river debouching from the Himalayas will deposit the greatest portion of its load near the point where it leaves the hills, and that as the load of silt sinks into the crust the amount of crustal subsidence along the course of the river will be greatest where the river leaves the hills.

Let us take two contiguous Himalayan rivers, the Ganges and the Jumna ; the Ganges leaves the mountains at Rikkikesh, the Jumna leaves them at

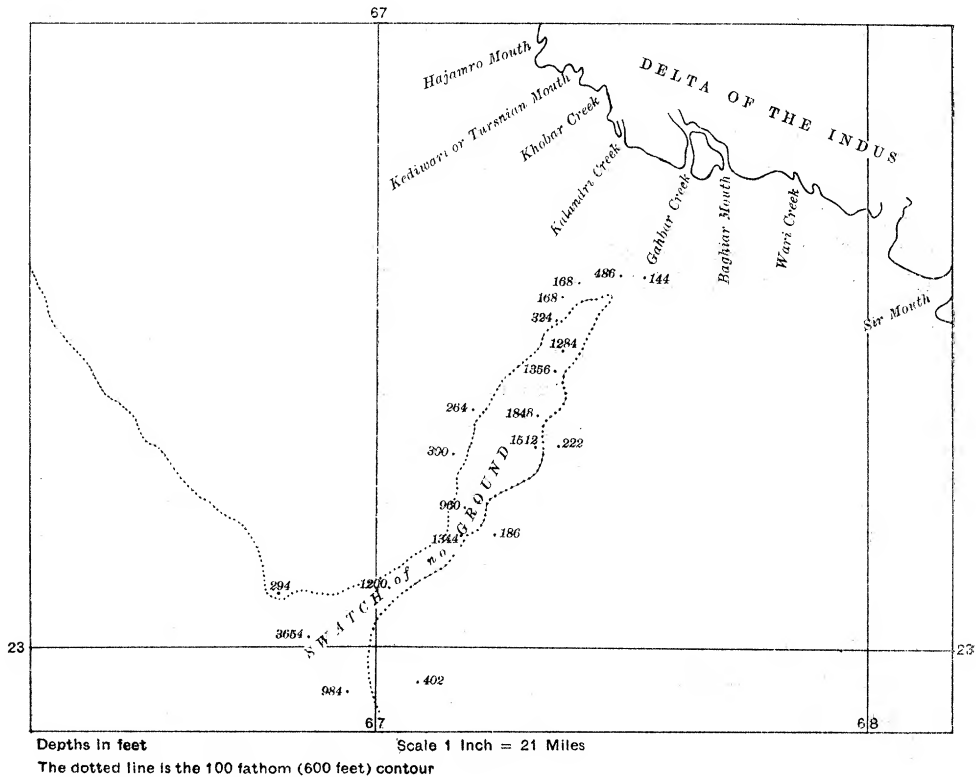


FIG. 3.

Kalsi. Rikkikesh is 45 miles from Kalsi. The great load of silt brought down by the Ganges will (according to the theory of "depression by weight") cause a sinking of the crust near Rikkikesh, whilst the load brought down by the Jumna will cause a subsidence near Kalsi. But why should these silt-loads of the Ganges and Jumna cause subsidence of the crust throughout the 45 miles that intervene between Rikkikesh and Kalsi ? The geodetic observations have led us to believe that there is a deep invisible trough skirting the foot of the mountains ; we have no geodetic data in support of the view that the depth of this trough increases at

points where rivers emerge from the hills and decreases at intermediate points. The geological theory demands not a continuous trough in the crust, but a series of basins under Hurdwar, Kalsi, and similar riverain points.*

9. *Fifth Consideration: The Hidden Troughs of the Punjab.*

Mr. Oldham, dealing only with the eastern half of the Indo-Gangetic trough (see fig. 1), shows in his diagram that the alluvial deposits of a river are a maximum at the foot of the mountains and decrease gradually as the river recedes from the mountains. On its northern margin, he writes, the depth of the alluvium is great, on its southern margin its thickness is small; the depth, he assumes, "decreases gradually from north to south." But let us apply this hypothesis to North-Western India, to the plains of the Indus and Sutlej (see fig. 1). The Punjab is bounded on the north-west by the Sulaiman range and on the north-east by the Himalayas (fig. 1). We have reason to believe, though the evidence is not yet complete, that a trough filled with alluvium skirts the feet of both ranges; this deficiency of matter runs round the edge of the Punjab plains; in the centre of the Punjab is an excess of matter. The alluvial deposits over the Punjab have, however, been brought down from the Himalayas by the Indus, Jhelum, Chenab, Ravee, Beas, and Sutlej (fig. 1). Where the Ravee leaves the Himalayas, near Pathankot, a deep hidden trough exists; this trough should, according to the "depression by weight" theory, become shallower as the Ravee crosses the Punjab; it does become shallower for a certain distance, but on the west of the Punjab becomes deeper again, namely, along the foot of the Sulaiman Mountains;† this deepening demands, according to Mr. Oldham's theory, a new source of alluvial deposit, and as we found the source of the eastern deposits in the Himalayas so we naturally turn to the Sulaiman Range to supply the western ones; but the rivers of the Sulaiman have always been insignificant, compared with those of the Himalaya, and their alluvial deposits have been trifling compared with those of the Indus; and we find that whereas the association of a trough of deficient density with the foot of a mountain range holds good on both sides of the Punjab, the association of this trough with sources of alluvial deposit holds good only on one side; if, therefore, the weight of the alluvium was not the cause of the trough below the Sulaiman Mountains, it is difficult to argue that it must have been the cause of the trough below the Himalaya.

* This theory will be tested geodetically.

† See Plate 5 of Lenox-Conyngham's 'Pendulum Operations in India.'

10. *Sixth Consideration : The Bore-Holes.*

The plains of Northern India are deposits of silt brought down by rivers from the Himalayas. Bore-holes have been sunk and remains of organic life found buried at great depths in the silt; it has been assumed that the rock-floors underlying the Indus-Ganges valleys have been continually sinking under the increasing weight of the deposits. Both on the west and on the east, long, deep, narrow, submarine troughs extend out into the oceans in continuation of the Indus and Ganges valleys. The waters of the Indus and Ganges are continually pouring silt into these troughs; amongst the silt are remains of organic life that once flourished at sea-level—plants, shells, bones—and these are being deposited at great depths in the troughs. The assumption that organic remains found at depths in bore-holes must have been originally deposited at sea-level is thus not justified. The simplest explanation is that the plains of Northern India are concealing a sub-crustal crack, that the submarine troughs are continuations of the crack, and that as the crack has opened and grown deeper, the deposits filling it up have been continually sinking to lower levels.

11. *The Subterranean Form of the Indo-Gangetic Trough, the Slope of its Rock-walls, the Depth of its Rock-floor.*

In my original paper on this subject I emphasised the fact that a band of low density exists in the crust along the northern border of the Indo-Gangetic trough. I thought that this band of low density indicated an opening in the Earth's crust, and this view was strengthened by the topographical appearance of the Indo-Gangetic trough, the parallel sides of which give the idea of a crack in our planet (see fig. 1). But I did not presume to deduce any value for the depth of the trough from the geodetic results.

It is true that I did refer on one occasion to a possible depth of 20 miles, but this figure was independent of the geodetic results: I suggested 20 miles for the depth of the crack, because that is the depth at which earthquakes have their origin in our time.

The geodetic results justify the conclusion that a line of low density exists; Mr. Hayford writes to me from America:—

“Your present work is certainly very effective in showing clearly the existence of a belt of defective density and a belt of excessive density each crossing India. No future investigation will contradict those two conclusions.”

The line of low density is proved, but we cannot determine the exact form of the trough. I admire the skill with which Mr. Oldham has grappled with

the geodetic problem, but still the figures in his paper, published by the Royal Society, have all been based on three uncertain assumptions:—

Firstly, he has had to assume that the Himalaya Mountains are everywhere in complete local isostatic equilibrium; secondly, he has had to assume certain values for the densities of alluvium and rocks at great depths; and, thirdly, he has had to assume an intimate knowledge of deep-seated geological formations in a foredeep, the origin of which is unknown.

There is evidence to show that the Himalayan mass is largely compensated, as a whole, but when we come to numerical calculations it is unsafe to assume that the compensation is locally effective.*

Mr. Oldham has told us that 15,000 to 30,000 feet of sediment have been deposited along the foot of the Himalayas, and that these deposits have sunk into the Earth's crust, and created a trough by their weight. These deposits, lying in their self-made trough, he calls the "invisible topography," and he tells geodesists that they must make allowance in their calculations for the invisible as well as for the visible topography. But what happens when these deposits are disturbed? Geologists have found that these deep deposits have in places been elevated above sea-level.

Mr. Oldham himself writes in the 'Geology of India,' p. 470: "The Siwaliks now form low hills, in which these once horizontal deposits have been disturbed, elevated, and exposed to denudation."

Where, then, is his invisible topography? Is it lying in its bed undisturbed, or has it been uplifted? If it has been uplifted, has the old rock which the alluvium depressed been uplifted also. In his calculations Mr. Oldham has assumed the existence of undisturbed deposits, when the latter are known to have been elevated. On p. 40, 'Proceedings of the Royal Society,' vol. 90, Mr. Oldham draws the deepest part of his undisturbed trough exactly under the zone where the deposits have been elevated.

If we observe the plumb-line or pendulum at the Earth's surface, we constantly obtain results that have no apparent topographical or geological explanation; we find the plumb-line deflected away from visible mountains, we find it deflected towards oceanic hollows, we even obtain abnormal results when observing upon desert plains. It is evident that there exist invisible deep-seated causes. The calculation of the depth at which these invisible causes are situated is a complicated problem. If we make different assump-

* A large floating iceberg is in equilibrium *as a whole*; its visible masses above sea-level are compensated by invisible masses below sea-level *as a whole*. But every ice pinnacle of the berg is not individually and locally compensated by a corresponding root of ice. Under the Himalayan station, Mussooree, height 6924 feet, the compensation appears to amount only to three-fourths of the visible mountain.

tions concerning the dimensions and densities of a hidden disturbing cause, any number of different values of the depth can be found to satisfy the geodetic results.

Mr. Oldham has taken the plumb-line observations of a few stations and has endeavoured to show that these observations can be explained on the hypothesis that the Gangetic trough is $3\frac{1}{2}$ miles deep.

It is easy, however, by slight changes in the assumptions to obtain greater values for the depth of the foredeep than $3\frac{1}{2}$ miles, and I do not know why the smaller value should be preferred to the greater.

Mr. Oldham, wishing then to show that a rift would not produce effects in accordance with geodetic results, assumes a rift of symmetrical section, 17 miles deep, 5 miles wide.* I agree that this assumed rift does not accord in any way with the geodetic results. The only references that I made in my memoir to the form of the Indo-Gangetic rift were as follows:—

(i) “The Himalayan side of the rift appears to be a steep wall, the southern side has a gentle slope” (p. 3).

(ii) “There has been a succession of cracks in successive sub-crustal shells. On each occasion that the rift has become deeper, it has opened further north than before. Only by such an hypothesis am I able to explain the steepness of the wall on the north side of the rift and the gentleness of the slope on the south side” (p. 7).

The above extracts will show that the idea of a symmetrical rift, 17 miles by 5 miles, has not been derived from my paper.

The Himalayan foredeep has, I think, the same form as the great deeps off the coast of Asia; the following extracts are borrowed from Prof. James Geikie's recent work on ‘Mountains: their Origin, Growth, and Decay’:—

“On the accompanying map, a section across the Pacific from Japan to North America shows the Tuscarora deep of the great Japanese trough. It will be observed that the sea-floor descends from the coast at a somewhat high angle to the depth of 4600 fathoms, after which it rises with a much gentler gradient, until the level floor of the ocean is reached at a depth of a little over 2000 fathoms. The deepest part of the trough, therefore, lies relatively close in shore or at the foot of the continental escarpment.

“The bottom of the Aleutian trough is somewhat irregular, varying in depth from 3000 to 4000 fathoms. It extends from the Alaskan Peninsula along the whole front of the arc of islands, and is almost continuous with the enormous Japanese depression. The latter skirts the outer coasts of the Kurile Islands, Japan, and the Bónin Islands, with a depth ranging between

* Such dimensions as 17 miles by 5 miles were not mentioned in my paper.

3000 and 4000 fathoms, the deepest part of the trough throughout its whole extent lying nearest the land.

"The Philippine trough begins opposite the Riu Kiu Islands, and extends along the whole eastern margin of the Philippines to Tular Island, at a depth of 3000 to 4700 fathoms, the greatest depths, as in all other cases, lying closest in shore."

Geodetic observations have led us to infer that the rock-floor of the Himalayan foredeep has a steep slope on the side of the mountains and a gentle slope on the opposite side. It would, however, be unsafe to assume that these surface forms are the results of superficial causes. The compensation of mountains and continents extends, according to Mr. Hayford, to a depth of 70 miles; the Himalayan and Japanese foredeeps are both lines of constant seismic activity, and the earthquakes are believed to occur at depths exceeding 20 miles. The forms of the Himalayan and Japanese foredeeps are possibly the effects at the Earth's surface of deep-seated sub-crustal movements.*

The idea I have formed of the Indo-Gangetic trough and of the Tuscarora deep is that sub-crustal shells have been cracking under tension, and that the cracks have been followed by sub-crustal movements (due to shrinkage at considerable depths) towards the side of the mountains. The cracks may have become filled, partly by lava flows from below, partly by slow rock-flows from the sides, and partly by débris from above. All that we know of the materials filling the trough is that they are abnormally light.

Before I leave the question of the form of the trough, I must refer for one moment to the position of that point at which the depth is a maximum. Mr. Oldham makes this point actually under the Siwalik Hills (see his diagram on p. 233). The geodetic observations lead me to place the greatest depth of the trough altogether south of the Siwalik Hills, and many miles south of Mr. Oldham's position.

In the 'Geological Magazine,' vol. 10, No. 594, pp. 532-536 (December, 1913), Mr. Oldham wrote as follows:—

"Every observer, in every part of the range which has been visited, has found evidence of compression in precisely that zone where Colonel Burrard's postulate demands extension."

Geologists have, it is true, found evidence of compression in the mountains,

* The width of the Himalayan foredeep varies from 350 miles in North-West India to 100 miles south of Nepal. Captain Couchman, in charge of the pendulum observations, is of opinion that the deepest part of the Himalayan foredeep is not where the alluvial deposits stand highest above sea-level, but is opposite to Eastern Nepal, where the Himalayan range is at its highest.

but not in the "foredeep"; my postulate demands extension in the foredeep only, not in the mountains. I submit that the yielding to tension under the foredeep has been the cause of the compression in the mountains.

Whilst I have no means of determining either the depth of the Himalayan foredeep, or the densities of the rocks and débris that are filling it, I give in fig. 4 (*b*) a rough diagram to illustrate my idea of the form of the trough.

The figure 4 (*a*) is copied from Mr. Oldham's paper, p. 40, 'Proceedings of the Royal Society,' vol. 90 (1914). M and N represent the Himalayas, R to S represents the Siwalik foot-hills. This figure 4 (*a*) illustrates Mr. Oldham's

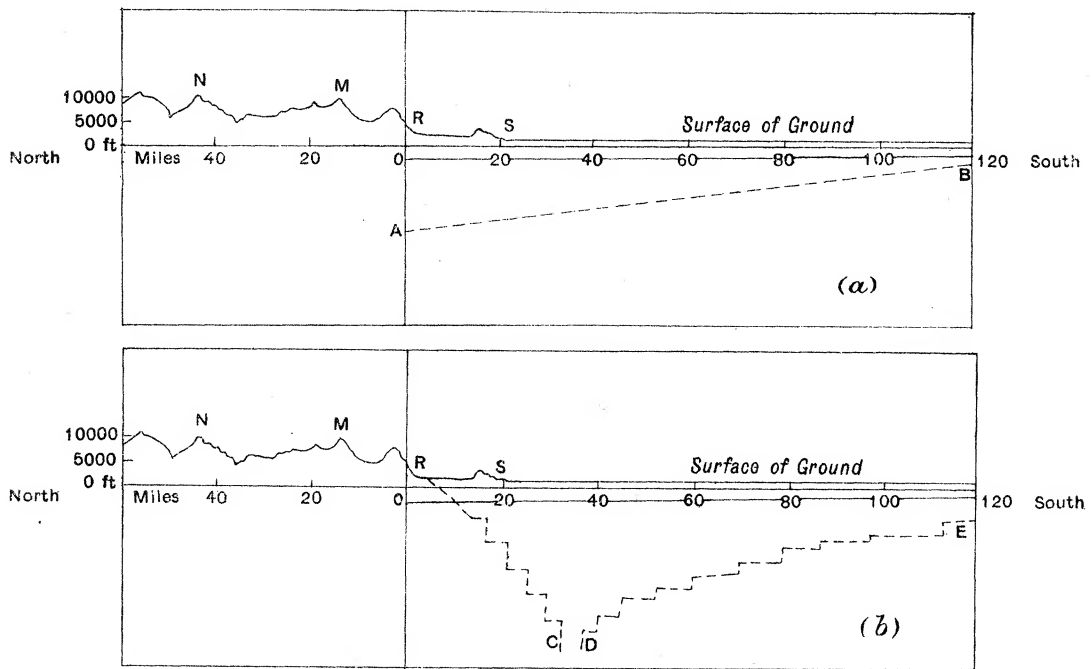


FIG. 4.

explanation of the foredeep. The bottom of his foredeep is shown by means of the dotted line AB. His idea of the form of the foredeep is RAB. According to his explanation river deposits have sunk by their weight to the depth of the line AB, and RAB is the "invisible topography." He believes that the Himalayas, NM, have moved southwards and have crumpled up the Siwalik foot-hills at R and S. He places the deepest point of the foredeep at A, *i.e.* at the northern edge of the Siwalik foot-hills.

Fig. 4 (*b*) illustrates my idea of the form of the foredeep, which I have drawn with a dotted line. I place the deepest point of the foredeep at D, *i.e.* south of the Siwalik foot-hills. The depth of D is unknown.

The explanation which I beg to offer is that the Earth's figure and outer shells have been under tensile strain and that the foredeep has opened from E to C. As the sub-crust at C has been forced to move northwards, the Himalayas at M and N have been uplifted vertically, and the Siwalik deposits at S and R, after sinking into the rift, have been uplifted and pressed against the Himalayas.

12. *The Hypothesis of a Rift.*

I am indebted to Mr. J. de Graaff Hunter, M.A., Mathematical Adviser to the Survey of India, for the following note upon the cooling of the Earth and upon cracks in the sub-crust.

Note on Cooling of the Earth and Cracks in Sub-crust.

By J. DE GRAAFF HUNTER, M.A.

It appears to me that the early state of the Earth must have been such as described by Lord Kelvin.*

The state presupposed is a globe in a fluid state, on account of its high temperature, losing heat by radiation; this is the first stage. I think it is unnecessary to go further back and discuss the most probable way in which this state was arrived at; it appears a highly probable early state. The subsequent history of such a globe would be as follows:—First of all an outer layer would cool and eventually solidify. If, as occurs in practically all known substances—and surely in the great bulk of the materials which make up the Earth—the material of the crust contracts with cooling, it accordingly becomes more dense than the fluid below it, and it breaks up and sinks into that fluid. Probably it melts again, but by doing so it chills the surrounding fluid to some extent. This process seems to be continuous until a solid core is formed; and this core will keep on increasing in size as the successive surface crusts fall in, until we eventually arrive at the second stage—a solid globe of nearly uniform temperature. The uniformity in temperature is due to the convection effect of the successive sinking of the crust and rising of molten matter from below.

When the whole globe is solidified, this convection ceases and the result is a very rapid cooling of the outer crust, which now depends for its heat on conduction from the interior of the globe. After a comparatively short time the crust approximately reaches its final temperature, which depends on the exchange of radiation between the Earth and other bodies of the universe. This is the third stage. Considerations of radioactive substances may slightly modify this result, but not in a way which affects the subsequent argument. During this process of cooling of the crust, cooling below has also been going on, but at a much smaller rate. The contraction, which has already been assumed to accompany cooling, must during the third stage have thrown the crust into a state of great *tension*. We have to consider the crust cooling rapidly from a temperature of the order of that of melted rock to a temperature such as prevails at present at the Earth's surface. Inevitably cracks must occur. This state of affairs is prior to the existence of oceans, for the temperature until nearly the end of this state would be above the boiling-point of water. There would not be any rush of water into such cracks, but gravity

* 'Mathematical and Physical Papers,' vol. 3, Art. XCIV.

would be sufficient to partially close them up by the upper edges of the crack breaking off, until the slopes attained the angle at which equilibrium was possible. Later on, the water would condense and find its level round the globe. By so doing it seems probable that the level (equipotential) surfaces throughout the globe would be disturbed and further fractures might take place, probably with a tendency to follow parallels of latitude.

By this time the fourth stage has begun, in which the surface of the Earth would be, as regards temperature and existence of oceans, similar to what it is now. It would not be an exact geometric figure, but I imagine the main features would be continents and oceans and the cracks which occurred in the third stage, and that there would not be any appreciable mountains. The increase of temperature with depth near the crust would at the beginning of the fourth stage be very much more rapid than it is now, and the material a little way in from the surface would continue to cool at a rate which was now greater than the rate at which the crust would be cooling, the crust having now approximately reached a steady temperature. The inner earth would then proceed to contract more rapidly than the crust. It would itself crack, and the most likely places for such cracks to occur would be those already exposed to air or ocean by the cracks of the outer crust. In such cases the *débris* which had fallen into the outer cracks would sink lower into the earth. This cooling of the portion below the outer crust would result in one of two things, or a combination of them, namely (1) the crumpling of the crust and (2) the slipping of the crust and attendant partial closing up of its cracks. *These surface cracks, however, could never be wholly closed up by contraction of interior matter until the whole Earth had reached a steady (low) temperature.*

As time went on, lower and lower levels would reach the state of contracting more rapidly than those both below and above them, resulting in cracks in the particular layer and a tendency to crumpling, or closing up of cracks, in the upper layers. We are apparently now at the stage when this effect has penetrated to the comparatively small depth at which earthquakes have their origin. It appears that, as this depth increases, the chances of crumpling of the upper layers diminish and that of the partial closing of cracks increases. But, as I have said above, the cracks cannot be entirely closed up by contraction alone until the whole Earth is cooled.

A further effect is to be expected. The cracks which are formed in any layer, except a few of the uppermost, will in due course be partially filled up by fractured material falling down from an upper layer; and with contraction in still lower layers (due to further cooling) will be entirely closed. Still further contraction below will inevitably cause crumpling, for there is now no alternative in the way of cracks closing. This crumpling in the lower layers must cause a vertical lifting of the surface layers, which will then form mountains. The cracks in the surface layer will not, in the main, be closed by this upheaval, for the area of the lower layers has been increased by crumpling, and the surface layer must either stretch or crack to accommodate itself to the enlarged area on which it rests. In this way new cracks might actually open, while mountains were being formed in the outer crust.

It appears impossible to assign any limits to the depths up to which this effect might occur.

The cracks on the outer surface could never be wholly filled up. They would only be partially filled by fractures in the third stage and by the products of denudation in the fourth stage.

The following is an extract from Prof. Shaler's 'Comparison of the Features of the Earth and Moon,' p. 8:—

"The surface of the moon exhibits a very great number of fissures or rents,

which when widely open are termed valleys, and when narrow, rills. Both these names were given because these grooves were supposed to have been the result of erosion due to flowing water. The valleys are frequently broad; in the case of that known as the Alpine valley, at certain places several miles in width; they are steep-walled, and sometimes a mile or more in depth; their bottoms, when distinctly visible, are seen to be beset with crater-like pits, and show in no instance a trace of water-work, which necessarily excavates smooth descending floors such as we find in terrestrial valleys. The rills are narrow crevices, often so narrow that their bottoms cannot be seen; they frequently branch, and in some instances are continued as branching cracks for 100 miles or more. The characteristic rills are far more abundant than the valleys, there being many scores already described; the slighter are evidently the more numerous; a catalogue of those visible in the best telescopes would probably amount to several thousand.

“It is a noteworthy fact that in the case of the rills, and in great measure also in the valleys, the two sides of the fissure correspond, so that if brought together the rent would be closed. This indicates that they are essentially cracks which have opened by their walls drawing apart.”

The “canals” of the planet Mars have given rise to much interesting discussion. I have no right to express an opinion upon this subject, but as astronomers have differed widely in their views, I may perhaps be permitted to invite the attention of students of Mars to the rifts on the Moon’s surface and to the apparent rifts on the Earth’s surface, and to ask whether the canals of Mars may not be openings in its outer crust.

Mr. Hunter, in his note which I have quoted above, has considered a cooling globe, and has shown that it is liable to crack. This liability will be increased by the strains to which the Earth’s figure and upper crust are subjected. If the Earth’s rotation has decreased in the past, the sphericity of its figure must have decreased also. The superfluity of rock accumulated at the equator under a higher rotation velocity could not have moved to the poles without great distortions of the rock surface occurring.

It has been estimated that the Earth picks up from 10 to 20 millions of tons of additional matter from space in the shape of meteors every year. If at any time in the past the Earth was ever struck by a very large body from space, ages may have ensued before the Earth’s figure was able to accommodate itself to the new conditions. In geological history there appear to be epochs, especially the Permian and the Cretaceous, when large changes of figure began, and it may have been that some abnormally large addition of rock was then picked up by the Earth from space.

Even the accumulation of ice at the poles in the glacial epoch may have

been sufficient to affect the spheroidicity of the Earth, and to set up strains in its outer shells.

13. *Departures from Isostasy.*

It has been shown by geodetic observations that the Earth's crust is in a condition approaching isostatic equilibrium. If any departure from isostasy occurs, the Earth's figure becomes subjected to strains, and its surface becomes liable to crack (or to stretch). A considerable departure from isostasy cannot persist indefinitely; the force of gravitation and the Earth's rotation are always tending to produce complete isostasy. When isostasy is disturbed by the irregular cooling of the sub-crust, or by the slowing down of the Earth's rotation, or by the impact of meteors, or by the conversion of equatorial water into polar ice, equilibrium can be restored by the compression of the crust in some regions and by stretching of the crust in others. Crustal tension and crustal compression are among the means by which isostasy is maintained.

The readjustments in the isostasy of a continent that become necessary, as the Earth undergoes changes, may bring about disturbances in the isostasy of smaller regions.

In India, the Indus-Ganges trough appears to have been opening northwards, and the Himalaya Mountains seem at the same time to have been undergoing elevation along the northern edge of the trough. If this view is correct, a certain amount of rock must have been moved northwards out of the trough into the mountains. The northward movement may have been caused by the cooling of the Earth or by readjustments of its figure or mass to new conditions. The disturbing effects upon local isostasy of this northward movement have been partially counteracted by denudation, for, although rock-mass may have been moved northwards by the opening of the trough, rivers have been bringing silt southwards from the rising mountains and pouring it back into the trough.

In this paper I have discussed the hypothesis that the Earth's crust is being depressed by the weight of riverain silt deposited upon it, and it may not be out of place to attempt to discover from observation the weight of actual loads which the Earth's crust is seen to be supporting.

Colonel Lenox-Conyngham writes: "Under the Himalayan station of Mussooree, height 6924 feet, there appears to be standing above sea-level an extra uncompensated mass equal in bulk to about a quarter of the visible mountain."

This is Colonel Conyngham's deduction of the most probable result; he emphasises the fact that there are elements of uncertainty in the calculation.

A considerable departure from isostasy is exhibited by the Ranchi Plateau. This plateau forms part of the Vindhya Mountains, and is a relic of an ancient tableland; it is situated immediately south of the Indus-Ganges trough in longitude 84° , opposite to the Himalayan peaks of Mount Everest and Dhaulagiri. Ranchi lies near the crest of the "hidden chain" of excessive density. The pendulum observations seem to indicate that the Ranchi Plateau is mainly supported by the rigidity of the Earth's crust; and the plumb-line observations show that there is a considerable excess of mass south of the Ganges at Ranchi. The Earth appears to be supporting this load without appreciable deformation.

As, however, certain geodesists have modified to a slight extent Prof. Helmert's formula for the normal value of gravity, and as the calculation of any departure from isostasy is dependent upon that formula, I asked Colonel Lenox-Conyngham to give me his opinion concerning the load supported at Ranchi. He considers that the Ranchi mass may possibly not be wholly supported by the crust's rigidity, but that probably half of it is. If this cautious estimate is accepted, then the Earth is strong enough to sustain a weight of 1000 feet of rock (density, 2.67) over an area of two square degrees (8500 square miles) without yielding.

I have now given my reasons for thinking that the hypothesis of a sub-crust opening under tension is more in accordance with observed facts and is more deserving of consideration than the idea of strata sinking under their own weight.
